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RESEARCH PAPER

Effect of varying soil water stress regimes on nutrient uptake and biomass production in *Dalbergia sissoo* seedlings in Indian desert

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Abstract: One-year-old seedlings of *Dalbergia sissoo* from a single provenance were planted in non-weighing lysimeter tanks in July 1998 with a view to provide optimize irrigation parameters in desert areas. Varying water regimes were maintained by re-irrigating the seedlings at 36.2 mm (W_1), 26.5 mm (W_2), 20.2 mm (W_3) and 18.1 mm (W_4) treatments when the soil water content decreased to 7.56%, 5.79%, 4.44%, 3.23% in the respective treatments. Height, collar diameter, number of leaves and leaf area were highest ($p < 0.01$) for the seedlings irrigated at W_1 level. Above-mentioned growth parameters did not differ between W_1 and W_2 treatments but the seedlings in W_2 level had highest biomass per liter of water use (i.e., water use efficiency, WUE). Irrigation levels of W_3 to W_5 negatively affected seedling growth, biomass production and nutrient accumulation. Soil water availability below W_2 level (i.e., 5.79%) caused an increase in percentage of root biomass to the total biomass of the seedling. However, there was a decrease in percentage of leaf dry biomass in W_3 and W_4 treatments and in percentage of stem dry biomass in the seedlings of W_5 treatment. Seedlings in W_5 treatment survived till at soil water potential of –1.96 MPa. Limitation of soil water availability in W_3 and W_4 treatments affected growth and biomass production of *D. sissoo* seedlings. W_2 level was best for growth and biomass production in which water use efficiency was highest. Therefore, better growth and biomass production of *D. sissoo* seedlings could be obtained by irrigating the seedlings at soil water content of ≥5.79% in the loamy sand soil.

Keywords: arid region; irrigation levels; seedling survival; soil water content; tree growth

Introduction

Rapid industrialization and irrational use of land and biotic resources cause deforestation and desertification. Afforestation and appropriate plantation management are the best options to increase productivity and to meet the requirement of fodder and fuel in dry region (Halldorsson et al. 2008; Singh and Goel 2008). However, soil water and nutrient availability are the main limiting factors to growth and productivity of plants in dry areas. The situation becomes more adverse because of low and erratic rainfall (100 to 300 mm per year), high evaporation, air and soil temperature and wind speed and low water holding capacity of arid soil (NAPCD 2001). In northwestern region of India, there are naturally growing species, such as *Prosopis cineraria*, *Tecomella undulata*, *Zizyphus nummularia*, etc. (Singh 2008). However, they are comparatively slow-growing species. A number of researchers have emphasized the need for developing more fast-growing species with high commercial value. *Dalbergia sissoo* Roxb. Ex D.C. Prodr is an important species of Indian subcontinent and other tropical countries (Chaturvedi et al. 1988; Lemmens 2008). This species was planted along the canal banks with the other species by the state forest department, Rajasthan along Indira Gandhi Nahar Project (IGNP) in north-western Rajasthan. However, our field investigation to IGNP areas and other regions of the Rajasthan state revealed that this species had a significant mortality. Some researches in other regions of the subcontinent reported a decline of *Dalbergia sissoo* due to the occurrence of fungi such as *Fusarium* sp. and *Ganoderma lucidium* in the roots and stems of *D. Sissoo* trees; but Sah et al. (1999, 2002) reported that the soil texture is considered as the main reason of increasing mortality rate in *D. sissoo* plantation in Nepal. However, soil water stress in the desert environmental conditions of India probably caused water stress in trees and higher mortality rate. There are many reports on the response of *D. sissoo* towards sulphur application (Mazhar et al. 2006), phytoremediation of seleniferous soil (Dhillon et al. 2008), reclamation of coalmine overburden dumps (Maiti 2007) and wastewater utilization (Singh and Bhati 2003; 2005). However, there are few studies on optimum level of irrigation and its relations with biomass production of *D. sissoo*. Careful examination of soil water depletion and re-irrigation to maintain the seedlings at different range of soil water availability may provide information about frequency of irrigation. This will help in increasing the chances of seedling survival as well as productivity of *D. sissoo* under controlled supply of water.

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This study aims at providing optimize irrigation parameters (frequency and quantity), minimizing water losses in sandy soils and enhancing seedling establishment, growth and biomass of *D. sissoo*.

Materials and methods

Site conditions

Experiment was carried out at the experimental farm of Arid Forest Research Institute (AFRI), Jodhpur (latitude 26º13'52.4"–26º14'11.8"N, longitude 73º03'43.3"−73º01'57.5"E). Among the three prominent seasons (i.e., summer, winter and monsoon (rainfall period), summer period is the most dominant characterized by high temperature from March to mid-July. The period from mid-July to September is characterized by the monsoon, when most rainfall occurs. In the winter period from November to February, the mean monthly minimum and maximum temperatures were 10.0ºC and 41.3ºC, respectively. The soil used in the experiment was a loamy sand (coarse loamy, mixed, hyperthermic family of typic haplocambides according to the US soil taxonomy) with pH 8.27, EC of 0.49 dSm^{-1} and a water holding capacity of 10.67% (w/w) at -0.03 MPa and 3.23% at -1.5 MPa. There was low level of KCl extractable nitrogen (12.59 mg kg^{-1}), Olsen's available phosphorous (10.68 $mg \cdot kg^{-1}$) and ammonium acetate extractable potassium (103 $mg \cdot kg^{-1}$) in soil.

Plantation and experimental design

One-year-old *Dalbergia sissoo* seedlings from a single provenance in the experimental nursery were planted in non-weighing lysimeter tanks (RCC tanks) **of** size (2 m×2 m×2 m) in July 1998. Soil structure in the lysimeter tanks was simulated with similar to the soil condition of a nearby field. Lysimeter tanks were filled with soil up to a height of 185 cm and a height of 15 cm was left in each tank for irrigation. A perforated galvanized iron pipe covered with glass wool was provided at the bottom of the lysimeter tanks so that excess water could be drain out. Experiment was laid in complete randomized design with three replications. There was one seedling in each lysimeter tank.

Soil water content and irrigation levels

Soil water content (SWC) was determined at - 0.10 MPa, - 0.50 MPa, -1.00 MPa and - 1.50 MPa pressure applied to pressure plat apparatus to develop relation between SWC and air pressure for defining treatments (Table 1). The experiment had five treatments comprising different irrigation levels according to soil water content at different pressures. Irrigation treatments were initiated in the first week of October 1998 after proper establishment of the seedlings. At the time of treatment initiation, soil of all the lysimeters was fully saturated by addition of water. Different irrigation levels were 36.2 mm (W_1), 26.5 mm (W_2), 20.2 mm (W_3) and 18.1 mm (W_4) throughout the experiment.

There was a control in which water was added to the tanks when leaves of the seedlings started drying or became leafless (W_5). Soil water content in a soil depth of 0–100 cm in Lysimeter tanks was monitored gravimetrically after obtaining the soil samples using mechanical auger with 5.0-cm diameter. Fresh weights of the above-mentioned soil samples were taken immediately using electronic top loading balance. The soil samples were then oven dried at 105ºC temperature and dry weights were recorded. Percentage of soil water content was calculated. The seedlings were re-irrigated when the soil water content approached to 7.56% (-0.10 MPa), 5.79% (-0.50 MPa), 4.44% (-1.00 MPa) and 3.23% (-1.50 MPa) in W_1, W_2, W_3 and W_4 treatments, respectively.

Table 1. Relation of suction pressure (-MPa) and soil water content (%) of the soil of lysimeter and corresponding quantity of water per irrigation (mm) in 0-100-cm soil layer

Treat-ment	Suction pressure(-MPa)	Soil water content (%)	Quantity of water per irrigation	
			(mm)	(Liter)
W_1	0.05–0.10	9.97–7.56	36.2	144.8
W_2	0.10–0.50	7.56–5.79	26.5	106.0
W_3	0.50–1.00	5.79–4.44	20.2	80.8
W_4	1.00–1.50	4.44–3.23	18.1	72.4
W_5	0.03–till death	10.67–till death	325.0 (one time)	1300

Growth observations

Height, collar diameter, leaf number, leaf size and leaf area were monitored monthly from September 1998 to June 2000. Leaf area was measured for 20 fully expanded leaves of each treatment in three replicates using Portable CI - 203 CA area meter, CID Inc. USA. Soil water content was determined gravimetrically in 0-100-cm soil layer continuously to maintain the treatment levels. Biomass estimation was done in June 2000 after 24 months of planting. One seedling of mean height and collar diameter was felled from each treatment (i.e., irrigation level) and separated into stem, branches and leaves for estimating biomass. Number of leaves was counted and leaf area was measured. Fresh mass of leaves, stem and branches was recorded immediately at the time of harvesting. Roots were excavated carefully, cleaned for soil adhered to the root and fresh mass was recorded. The primary root length and diameter of longest root are measured. The secondary root length was measured and averaged for five longest secondary roots. Dry mass of each of the seedling components was determined after the samples were dried in the oven at 75ºC. Total root volume was measured by water displacement method. Percent contribution of leaf, stem and root biomasses (i.e., biomass allocation in seedling parts) to the total biomass of the seedlings was calculated.

Leaf, stem (including branches) and root samples were collected from both harvested and the standing seedlings (non-destructive) in June 2000, dried at 75ºC and ground for nutrient analysis. Nitrogen (N) and phosphorus (P) were determined after sulfuric acid digestion. Potassium (K) was determined after triacid (HNO_3: H_2SO_4: $HClO_4$ in the ratio of 10:4:1) digestion using Fiastar autoanalyser system (Model Enviroflow –

5012, Tecator AB, Hoganas, Sweden).

Statistical analysis

All data were statistically analyzed using SPSS statistical package. Since the experiment was laid in complete randomized design, the data of height, collar diameter, leaf size, number of leaves and leaf area per plant were analyzed using a one-way ANOVA. Various growth parameters were used as the dependent variables. Irrigation levels were the main factors. Nutrient uptake was also analyzed using a one-way ANOVA. Correlation was performed for growth, biomass and nutrient uptake with irrigation levels and total quantity of irrigation. The means were compared by least significant difference (LSD) at $p < 0.05$ level.

Results

Irrigation frequency

Number of irrigation per year was highest in W_1 and lowest in W_4 while irrigating the seedlings when the soil water content approached to 7.56%, 5.79%, 4.44% and 3.23% in W_1, W_2, W_3 and W_4 treatments, respectively. The decrease in number of irrigation reduced the total quantity of water applied in a year from W_1 to W_4 treatments (Table 2). Thus frequency of irrigation was most in W_1 treatment (i.e., 14.4 and 19.2 number of irrigation per year in 1998-1999 and 1999-2000, respectively) and it decreased to the lowest in W_4 treatment (9.3 and 12.5 number of irrigation per year in the respective years). Total quantity of irrigated water in W_1 was 2.6-fold greater in 1998-99 and 2.2- fold greater in 1999-2000 than the respective quantity of water in W_4.

Table 2. Quantity and frequency (number of irrigation per year) of irrigation for the seedlings of *D. sissoo* at different ages in non-weighing lysimeters

Age (months)	Treatment	Frequency	Irrigation quantity ($mm \cdot a^{-1}$)	Total quantity of irrigation (mm)	(Liter)
3-12*	W_1	14.4	520.6	845.6	3382.4
	W_2	11.9	316.2	637.6	2550.4
	W_3	10.5	211.5	536.5	2146.0
	W_4	9.3	167.6	492.6	1970.4
	W_5	1		325	1300.0*
13-24	W_1	19.2	695.8	1541.4	6165.6
	W_2	15.3	404.1	1041.7	4166.8
	W_3	14.0	282.6	819.1	3276.4
	W_4	12.5	226.1	718.7	2874.8
	W_5	1		325	1300.0

Notes: *This amount was applied to maintain the soil of all the tanks at field capacity initially.

Seedling survival and growth

Seedlings in W_5 treatment can survive till at soil water potential (Ψs) of –1.96 MPa. Seedling mortality occurred below -1.96 MPa (Ψs). Height and collar diameter of *D. sissoo* seedlings did not differ ($p > 0.05$) at the time of treatment initiation i.e., first week of October 1998. However, height and collar diameter of seedlings at age of 24 months decreased ($p < 0.01$) with decreasing irrigation level. These variables were highest in the seedlings in W_1 and lowest in the seedlings of W_5 (Table 3). These growth parameters of the seedlings did not differ between in W_1 and W_2 treatments. However, there were reductions in height by 40% and in collar diameter by 38% in the seedlings of W_3 than in the height and collar diameter of the seedlings of W_1 treatment. Regardless of treatments, average increase in height during July to December was 67 cm (average of two years) as compared to 40 cm during January to June. The increase in collar diameter was 0.71 cm and 1.12 cm in the period from July to December and from January to June, respectively. Number of branches was significantly ($p < 0.001$) greater for the seedlings in W_1 treatment, but it reduced to lowest in W_5 treatment.

Table 3. Average height, collar diameter, number of branches, number of leaf and leaf areas of 24 months old *D. sissoo* seedlings affected by varying levels of irrigation

Treatments	Height (cm)	Collar diameter (cm)	Number of branches	Number of leaf	Leaf area per seedling (m^2)
W_1	390±10.41	7.1±0.19	80±0.88	5429±262	1.94±0.02
W_2	317±15.90	5.9±0.25	5±0.58	4165±184	1.54±0.01
W_3	263±1.67	4.4±0.06	35±0.57	2155±72	0.64±0.01
W_4	235±7.64	3.7±0.12	25±0.33	1842±69	0.45±0.02
W_5	190±0.00	2.1±0.00	19±0.00	17±00	0.02±00
P value	0.001	0.001	0.001	0.001	0.001

Notes: Values are mean of three replications with ±SE. W_1, W_2, W_3 and W_4 are 36.2 mm, 26.5 mm, 20.2 mm, 18.1 mm irrigation levels and W_5 is control (from 325 mm to 34 mm soil water).

Leaf growth and area

Soil water availability affected ($p < 0.01$) numbers of leaves and leaf areas per seedling of *D. sissoo* (Table 3). Both these variables were highest in the seedlings of W_1 treatment. Decrease in irrigation at W_2 treatment reduced number of leaves per plant by 23% and leaf area per plant by 21%, compared with that in the seedlings in W_1 treatment. But the reductions in leaf number and leaf areas per plant were by 60% and 67% in W_3 treatment and 66% and 77% in W_4 treatment, respectively. Relative reduction in leaf area per plant was greater than in number of leaf as a function of soil water stress. The numbers and sizes of leaves of the seedlings were the smallest in W_5 treatment. In June 2000, there were 17 numbers of leaves, which were drying due to drought stress in W_5 treatment.

Root growth variables

Irrigation levels influenced length of the primary and secondary roots. Primary root length increased in W_4 level of irrigation, whereas secondary root length increased in W_2 treatment (Table

4). The seedlings in W_5 level had shorter both primary and secondary roots. Primary root of the seedlings was increased by 15% and 35% in the W_4 and W_5 treatments, respectively. Secondary roots in W_2 level increased by 20 %, whereas those in W_3 level increased by 8 %, compared to those in the seedlings in W_1 level. Root volume of seedlings was highest (2170 cm^3) in W_1 treatment that reduced by 34% in W_2, 46% in W_3 and 76% in W_4 treatment. Root volume for the seedling of W_5 treatment was only 4 % of that in the seedling of W_1 treatment.

Table 4. Primary and secondary root length and root volume of 24 months old *D. sissoo* seedlings affected by varying levels of irrigation

Treatment	Root length (cm)		Root volume (cm^3)
	Primary	Secondary	
W_1	121	60	2170
W_2	123	72	1840
W_3	133	65	1180
W_4	134	51	530
W_5	72	39	77
F value	10.185**	10.013**	2.968*

Notes: W_1, W_2, W_3 and W_4 are 36.2 mm, 26.5 mm, 20.2 mm, 18.1 mm irrigation levels and W_5 is control (from 325 mm to 34 mm soil water). *is Significant at p< 0.05 and **is significant at P< 0.01 level.

Seedling biomass and its allocation in different parts

Varying levels of irrigation affected dry biomass of seedlings significantly (Table 5). Dry biomass production was highest (p < 0.01) in W_1 treatment. There was a reduction of 14 % in dry biomass for the seedling of W_2, whereas the biomasses of the seedlings in W_3 and W_4 treatments decreased by 50% and 70%, respectively as compared to that of the seedlings in W_1. Seedling in the W_5 produced 0.22 kg dry mass, indicating a reduction by 96% as compared to that in W_1 treatment. In general, dry biomass contribution of stem (that included branches also) was about 50% of the total biomass of the seedling. The roots and leaves each contributed to about 25% of seedling dry biomass (Table 5). However, the contribution of leaves to the total dry biomass of the seedling was 28% in W_1 and W_2 treatments. The biomass contribution of leaves of the seedlings was lowest in W_3 treatment in which stem contributed about 55% of total biomass. Percentage of biomass contribution of stem was lowest in the seedlings of W_5. Percentage of biomass contribution of roots of total biomass increased in the seedlings of W_4 and W_5 in which contribution of root to the total seedling biomass was 26% and 27%, respectively. Contribution of root to the total biomass was lowest (22%) in the seedlings of W_2.

Water use efficiency

Water use efficiency (WUE) of *D. sissoo* seedlings ranged from 1.21 $g·L^{-1}$ in W_2 to 0.17 $g·L^{-1}$ in W_5 treatments. There was an increase in WUE at mild soil water stress (W_2). However, WUE of the seedlings decreased when irrigation level decreased to W_3 and W_4 treatments. The WUE decreased to lowest value (i.e., 0.17 $g·L^{-1}$) in W_5 treatment.

Nutrient accumulation in seedlings

Total nutrient accumulation in 24-month-old *D. sissoo* seedlings was highest in W_1 treatment. In general, accumulation of nitrogen (N), phosphorus (P) and potassium (K) decreased with decrease in irrigation level or soil water availability. However, N and P accumulation increased in the leaf of the seedlings in W_2 treatment. The accumulation differed between leaf, stem and root. Nitrogen accumulation was significantly (p < 0.01) in leaf, compared to that in stem and root in all the seedlings, whereas P accumulation was highest in stem compared to that in leaf and root. Accumulation of K was highest in leaf in the seedlings of W_1 and W_2 treatments whereas it was highest in stem in the seedlings of W_3, W_4 and W_5 treatments. The accumulation of N, P and K was less than 50% in the seedlings of W_3 and W_4 treatments as compared to that in W_1. However, concentration of total nutrients accumulated reduced by more than 90% in the seedlings of W_5 as compared to those in the seedlings of W_1 treatment.

Table 5. Dry biomass ($kg·seedling^{-1}$), its allocation in seedling parts (%)* and water use efficiency (WUE) of 24 months old *D. sissoo* seedling affected by varying levels of irrigation

Treatment	Dry biomass ($kg·seedling^{-1}$)				WUE
	Leaf	Stem	Root	Total	($g·L^{-1}$)
W_1	1.64	2.88	1.38	5.90	0.96
	(27.8%)	(48.8%)	(23.4%)	(100%)	
W_2	1.42	2.53	1.10	5.05	1.21
	(28.1%)	(50.1%)	(21.8%)	(100%)	
W_3	0.52	1.38	0.63	2.53	0.77
	(20.6%)	(54.6%)	(24.9%)	(100%)	
W_4	0.44	0.86	0.46	1.76	0.61
	(25.0%)	(48.9%)	(26.1%)	(100%)	
W_5	0.06	0.10	0.06	0.22	0.17
	(27.3%)	(45.4%)	(27.3%)	(100%)	
F value	2.687*	3.001*	3.108*	2.944*	3.337**

Notes: W_1, W_2, W_3 and W_4 are 36.2 mm, 26.5 mm, 20.2 mm, 18.1 mm irrigation levels and W_5 is control (soil water from 325 mm to 34 mm). Values in parentheses indicate percentage of contribution of seedling parts to the total biomass.

Discussion

Irrigation frequency and seedling growth

D. sissoo seedlings growing at greater soil water availability utilized greater soil water, resulting in increased amount of irrigation in W_1 treatment, though greater water loss by surface evaporation at sufficient soil water cannot be ruled out. Bielorai et al. (1973) also recorded that increased amount of water per irrigation as well as higher number of irrigation resulted in higher evapotranspiration. In another study, frequent irrigation resulted in shallow root development in which most of the water

utilized by the plants was at soil layer of 0–40 cm (Myers et al. 1984). Less frequent irrigation resulted in root penetration for using water from the deeper soil layers. It was evidenced by decreased number of irrigation with decreasing irrigation levels from W_1 to W_5 (Table 2). At low irrigation level, soil water molecules are more tightly held in the soil profile thus reduced soil water availability and its utilization by seedling or surface evaporation. Thus reduced soil water use caused a reduction in the amount of irrigation. The increase in the frequency of irrigation and total water input in the second year as compared to that in first year was due to increase in demand of water use by the growing seedlings (i.e., increased seedling age) with relatively greater foliage as compared to the foliage in first year. However, total water use by 13-to 24-months-old seedlings in the present study was low as compared to the reported value of 910 to 1220 mm water use per year by *D. sissoo* (Sheikh 1974). This difference may be due to age and size of the plants in this study.

Significant differences in height and collar diameter of *D. sissoo* seedlings were due to variations in soil water availability at different irrigation levels. Ahmet et al. (2004) recorded that there was significant ($p < 0.01$) positive linear relations among irrigation water, plant water consumption, fruit traits and yield of *Cucurbita pepo* L. The observations of Bala et al. (2003) also indicated that there were significant differences in the growth parameters in the seedlings of *A. nilotica*, *E. camaldulensis* and *D. sissoo*. Better performance in the seedlings of W_1 and W_2 treatments as compared to other treatments might be due to more availability of the water and nutrients. It might influence the physiological processes that led to increase in growth rate. High soil water availability facilitated nutrients accumulation, leaf growth, leaf area and number of leaves which converted more solar energy and fixed more CO_2 to produce more photosynthates, and thus greater growth and biomass production (Ceulemans et al. 1993). Sufficient soil water availability in these treatments probably maintained cell turgidity and increased in leaf size and the over all biomass (Souch and Stephens 1998). A positive correlation between height (r^2 = 0.94, p < 0.01) and collar diameter (r^2 = 0.98, p <0.01) with quantity of irrigation further supported the water induced growth in *D. sissoo* seedlings. Pereira et al. (1992) reported that the seedlings supplied with near optimal amount of water and nutrient had higher growth rate than non-irrigating and unfertilized control seedlings of *E. globulus*. But decreased height and collar diameter in the seedlings in W_3, W_4 and W_5 treatments as compared to the seedlings in W_1 and W_2 treatments were due to low soil water availability affecting leaf number and finally leaf area per plant. Decrease in number of leaves, leaf size, leaf area and leaf biomass has been reported (Boyer 1988) under low soil water availability as observed in the present study. However, relatively greater decrease in leaf area per seedling as compared to the number of leaf in the seedlings in W_3 and W_4 treatments suggested that *D. sissoo* seedlings maximized leaf area by increasing number of leaf. This might be a strategy for greater photosynthates accumulation or reducing transpiration an adjustment towards drought stress. Highest root volume in the seedlings of W_1 was due to thickness and greater number of roots that facilitated water and nutrient absorption resulting in better growth of the seedlings as compared to those in the other treatments. Increase in the length of primary root in the seedlings in W_3 and W_4 treatments was to assure soil water extraction from the deeper soil layers. However, shorter root in the seedlings in W_5 treatment indicated that severe water stress negatively affected root growth. Furthermore, significantly low root volume in the seedlings in W_3 and W_5 treatments was due to decrease in number and growth of new roots that affected seedling growth under low soil water availability. Our results are consistent with the result of Smit and Driessche (1992) where similar soil water availability response was reported for the seedlings of *Pseudotsuga menziesii*.

Seedling biomass and its allocation in different parts

Highest dry biomass for the seedlings of W_1 treatment was believed to be due to increased soil water status that might influence the process leading to increase wood yield and facilitated growth of foliage to increase biomass. Hunter (2001) observed that irrigation increased dry weight linearly across treatments and the increase was 74% in the highest irrigation rate. Irrigation increased stem wood weight by 90% but branch and leaf weight by only 40% in *D. sissoo* and *Eucalyptus* spp (Hunter 2001). Wang et al. (2006) recorded highest growth and water use efficiency of potato irrigated at high frequency. Reducing irrigation frequency resulted in 33.4% and 29.1% yield reductions of potato in 2001 and 2002, respectively (Wang et al. 2006). Thus greater soil availability probably increased nutrient absorption, translocation and their accumulation in perennial parts that enhanced the capacity of the seedlings to form new leaf biomass (Peterson et al. 1993). Increased dry biomass of leaf as a result of greater soil water availability and nutrient absorption is evidenced by relatively higher contribution of leaf toward total dry biomass of the seedlings in W_1 and W_2 treatments. Li (1989) reported greater contribution of leafy shoots to the total dry biomass under sufficient resource availability, resulting in higher growth rate. Utilization of high proportion of assimilate in photosynthetic capital i.e., leaves has also been reported in other study (Ledig and Perry 1975). However, percentage of leaf dry biomass decreased to 21% and 25% in the seedlings in W_3 and W_4 treatments, respectively, suggesting a reduction in leaf growth/foliage biomass under soil water stress. It was due to increase in the percentage of dry biomasses of stem and roots. Relatively greater increase in biomass of root than in leaf and stem in the seedlings of W_3, W_4, and W_5 treatments was probably because of increasing root biomass with increasing soil water stress. Bongarten and Teskey (1987) observed an increase in root biomass at the expense of stem biomass when the seedlings were exposed to repeated drought cycles. But in the present study, the increase in percentage of root biomass was at the expense of leaf biomass in W_1, W_3, and W_4 treatments and at the expense of stem biomass of seedlings in W_5 treatment. Lesser percentage of root biomass in the seedlings of W_2 treatment, compared with that of the seedlings in other treatments, may be due to photosynthates allocation in maximising leaf biomass at mild water stress (Table 5).

The accumulation of N and P and WUE of the seedlings in W_2 level are highter than those in the other treatments, which also indicates that there is a greater biomass accumulation to stem and leaf (i.e., aboveground). However, at severe water stress, percentage of dry biomass allocation to root increased with simultaneous decrease in biomass of stem and leaf, which was more sensitive to water stress than the root.

Nutrient accumulation

Irrigation level and soil water availability influenced mobility of nutrients in the soil – root system and further transport to the seedling parts. Thus higher accumulation of N, P and K in the seedlings of W_1 and W_2 treatment was due to higher soil water availability (Table 6). Karlen et al. (1982) observed different responses to water stress in uptake patterns of K, Ca, and Mg because of differences in the mechanism by which these nutrients move to plant roots in soil. Therefore, decrease in irrigation level probably decreased availability and transport of nutrients particularly P and K. It was also responsible for variation in nutrient accumulation in seedling parts particularly in W_3, W_4 and W_5 treatments. The variation might also be due to mineral availability in soil, mode of use and transport of the nutrients from soil to the plant system and further to different parts of the seedlings (Al-harbi 1999; Maiti 2007). Highest amount (accumulation) of K in leaf of the seedlings in W_1 and W_2 treatments and in stem of the seedlings in W_3, W_4 and W_5 treatments may be due to higher availability of water in the former treatments facilitating transport and accumulation of nutrients in different parts of the seedlings and decreased transport of K under soil water stress in the latter treatments. Decreased K uptake was probably due to decrease in mobility of K in the soil and its diffusive flux under water stress. It is in agreement to the observation of Zeng and Brown (2000) in which K fixation increased, resulting in less availability of K in the soil under wetting-drying cycle.

Table 6. Total nitrogen (N), phosphorus (P), and potassium (K) (g·seedling^{-1}) in different parts from 24 months old *Dalbergia sissoo* seedlings under varying levels of irrigation

Treatment	N (g·seedling^{-1})				P (g·seedling^{-1})				P (g·seedling^{-1})			
	Leaf	Stem	Root	Total	Leaf	Stem	Root	Total	Leaf	Stem	Root	Total
W_1	43.56 ±1.74	35.93 ±1.49	29.16 ±0.92	108.66 ±0.43	3.23± 0.26	6.49 ±0.58	3.03 ±0.23	12.75 ±0.53	16.44 ±0.67	15.69 ±0.85	7.43 ±0.39	39.57 ±1.46
W_2	44.39 ±1.58	32.85 ±1.44	21.90 ±0.72	99.14 ±0.86	3.52 ±0.30	6.00 ±0.10	2.34 ±0.17	11.86 ±0.19	14.09 ±0.65	13.81 ±0.36	5.48 ±0.18	33.38 ±1.24
W_3	17.07 ±0.91	14.23 ±0.83	12.17 ±0.34	43.46 ±0.75	1.43 ±0.05	2.67 ±0.04	1.35 ±0.03	5.45 ±0.05	5.01 ±0.27	7.80 ±0.46	2.54 ±0.14	15.36 ±1.35
W_4	15.19 ±0.26	11.49 ±0.45	8.53 ±0.16	35.21 ±0.79	1.25 ±0.11	1.96 ±0.03	1.08 ±0.02	4.28 ±0.08	4.02 ±0.01	7.01 ±0.48	1.63 ±0.04	12.66 ±0.21
W_5	2.15 ±0.05	1.47 ±0.07	1.25 ±0.08	4.57 ±0.04	0.14 ±0.01	0.17 ±0.01	0.13 ±0.01	0.44 ±0.02	0.53 ±0.07	0.67 ±0.05	0.17 ±0.02	1.37 ±0.02
ANOVA value												
F value	2005.3	1596.4	2109.2	4628.6	526.4	395.2	455.3	424.7	256.2	316.4	245.2	222.6
P value	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Notes: Values are mean of three replications with ±SE. W_1, W_2, W_3 and W_4 are 36.2 mm, 26.5 mm, 20.2 mm, 18.1 mm irrigation levels and T_5 is control (soil water from 325 mm to 34 mm).

Conclusion

Results of this study indicated that drought stress seedlings in W5 survived till at a soil water potential with -1.96 MP. Seedling biomass in W5 treatment was negligible. Increase in irrigation level towards W4 and W3 treatments enhanced seedling growth, nutrient accumulation and biomass production. But at irrigation levels of W2 and W1, there were drastic improvement in seedling growth, leaf production, biomass and nutrient accumulation. Thus soil water availability of more than 5.79% (soil of 10.88 field capacity) was best for enhancing growth and production of D. sissoo. The seedlings irrigated at W3, W4 and W5 levels indicated best fit survival by increasing root length with simultaneous decrease in leaf biomass in W3 and W4 treatments and stem biomass in W5 treatments. Seedlings of D. sissoo tended to maximize leaf area through growing number of leaves. But it is interesting that D. sissoo did not follow the trend of water use efficiency (WUE) observed in the most xerophytic species in which WUE increased with water stress. At mild water stress, D. sissoo indicated highest WUE but at severe water stress WUE in this species decreased significantly. This showed moderate adaptability of D. sissoo seedlings towards water stress. This suggests that rapid growth and biomass production in D. sissoo can reach by irrigating the seedlings above 50% of field capacity in loamy sand soils

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